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(54) **Method and apparatus for automatic compensation of first-order polarization mode dispersion (PMD)**

(57) The effect of polarization mode dispersion that an optical signal experiences as it propagates through an optical transmission fiber is compensated for at a receiver using a birefringent compensator, in which the compensator automatically and adaptively generates a level of differential time delay that substantially equals the differential time delay that the optical signal experiences, but of different sign, and, therefore, essentially cancels out the undesired delay.

FIG. 1

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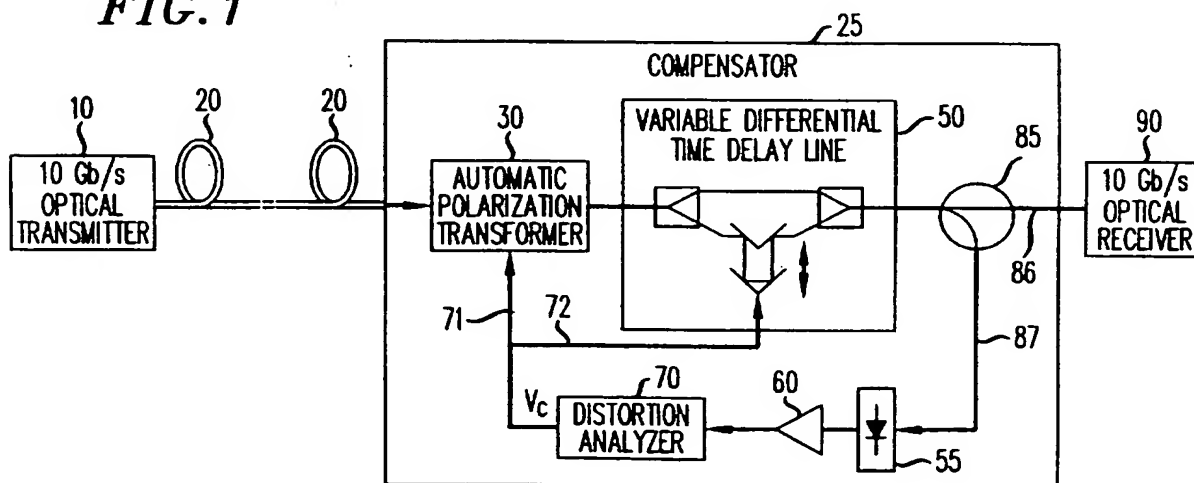
SUMMARY OF THE INVENTION:

[0009]   We deal with the foregoing problems and advance the relevant by providing apparatus which automatically adapts to the level of first-order polarization mode dispersion that may be present in an optical signal received from an optical transmission line. Specifically, we use a variable optical birefringence element which, responsive to receipt of the optical signal, generates a differential optical time delay between at least two selectable mutually orthogonal polarization states. An optical signal analyzer coupled to the output of the variable birefringence element, in turn, generates a control signal proportional to the total differential optical time delay that is present in an optical signal appearing at the output of the variable birefringence element. The control signal is supplied to the birefringence element to control the amount of differential time delay that is generated to control which orthogonal polarization states are selected.

[0010]   In this way, we automatically and adaptively generate a differential time delay that substantially equals the differential time delay that occurs in the transmission optical fiber, but of opposite sign, and, therefore, cancels out the undesired delay.

[0011]   These and other aspects of our invention are set forth in the following detailed description, corresponding drawings and ensuing claims.

BRIEF DESCRIPTION OF THE DRAWING:

[0012]   In the drawing:

FIG. 1 illustrates in block diagram form an illustrative system in which the principles of the invention may be practiced;

FIG. 2 is a block diagram of the distortion analyzer of FIG. 1;

FIG. 3 illustrates in graphical form a simulation of the feedback signal versus the total differential group delay for filtered, unfiltered and weighted 10 Gb/s pseudo-random sequences;

FIG. 4 illustrates in block diagram form another illustrative system in which the principles of the invention may be practiced;

FIG. 5 illustrates in graphical form a plot of the total differential group delay against the polarization transformation angle associated with a polarization transformer of FIG. 4;

FIG. 6 is a block diagram of an illustrative embodiment of an integrated circuit version of the differential delay line of FIG. 1; and

FIG. 7 is alternative embodiment of the system of FIG. 1 in which a signal scrambler is employed at the transmitter of an optical signal.

FIG. 8 illustrates a distortion analyzer that may be used to derive a feedback signal for the inventive PMD compensators in FIGs. 1 and 4.

DETAILED DESCRIPTION:

[0013]   Polarization Mode Dispersion (PMD) occurs in single-mode fibers as a result of residual birefringence in the fiber core and coupling of random polarization at various points along the fiber. The polarization transformation that occurs in the fiber may be modeled using a simple unitary 2x2 Jones matrix, $\underline{U}$, as shown by following expression;

$$\underline{U}(\omega) \quad = \begin{pmatrix} u_1(\omega) & u_2(\omega) \\ -u_2^*(\omega) & u_1^*(\omega) \end{pmatrix} \tag{1}$$

where u_1 and u_2 in general are complex functions which depend on the frequency, ω, of the optical signal and other physical parameters that influence the mode coupling in the fiber.

$$\tau_f = 2 \sqrt{\left|\frac{d}{d\omega}u_1\right|^2 + \left|\frac{d}{d\omega}u_2\right|^2}$$

is the Differential Group Delay (DGD) that causes the aforementioned differential time delay in optical signals that are not launched in one of the two Principal States of Polarization (PSP).

[0015] It can thus be appreciated from the above equations that a differential time delay, τ_f, occurs between the two PSP of the fiber. The differential time delay which an optical signal experiences as a result of propagating through an optical fiber may, therefore, be compensated for by introducing an opposite but equal amount of differential time delay, $\tau_c = -\tau_f$, at the output of the fiber, in accordance with an aspect of the invention. This may be readily done using an optical element having the following polarization dependent transfer function:

$$\underline{U}comp = \begin{pmatrix} e^{-j(\omega-\omega_0)\tau_c/2} & 0 \\ 0 & e^{j(\omega-\omega_0)\tau_c/2} \end{pmatrix} \cdot \underline{D}^{-1}(\omega_0) \cdot \underline{W}^{-1}(\omega_0) \qquad (7)$$

where $\underline{D}$ and $\underline{W}$ are the matrices shown in equation (3). The matrix Ucomp describes first order PMD (i.e., uniform birefringence) at an arbitrary orientation.

[0016] As mentioned above, PMD in a fiber may change with changes in time and optical frequency. This change in PMD may be dealt with, in accordance with another aspect of the invention, by varying the amount and orientation of the birefringence in the inventive compensator to adaptively compensate for the DGD in the fiber. An adaptive, variable-birefringence compensator may be readily realized by disposing a polarization transformer 30, for example, the polarization transformer described in U. S. Patent No. 5,212,743 issued May 18, 1993 to F. Heismann, which is hereby incorporated by reference herein, in series with an element 50 that generates variable linear birefringence (such as, for example, the polarization mode dispersion emulator, model PE3 available from JDS Fitel Inc.), as shown in Fig. 1. Such birefringence may be so generated, in accordance with another aspect of the invention, by splitting the signal at the output of the polarization transformer into two orthogonal linear polarization states corresponding to the two PSP of the fiber, and delaying each of the two polarization states by a variable amount of time, τ_c; using a respective delay line 50 as shown in FIG. 1. In fact, if the polarization transformation that occurs in polarization transformer 30 and the time delay in the variable differential time delay line 50 are properly adjusted such that polarization transformer 30 generates the polarization transformation described by the matrix W^{-1} expressed by equation (7) and such that variable differential time delay line 50 generates the differential time delay τ_c shown in (7); then a signal outputted by the compensator 25 will be free of the distortions caused by differential time delays occurring in transmission fiber 20.

[0017] Note that an optical element (such as, for example, a combination of properly aligned birefringent fibers connected in series) that generates variable frequency dependent birefringence may be used in a similar manner to compensate for signal distortions due to higher-order PMD. However, a polarization transformer in series with a variable birefringence compensator alone would not automatically adapt by itself to changes in the PMD of the fiber. Such automatic adaptation may be achieved, in accord with another aspect of the invention, by providing a feedback signal that controls the polarization transformation occurring in the polarization transformer 30 (i.e., the orientation of the variable birefringence) as well as the differential time delay in the variable differential time delay line 50 (i.e., the amount of linear birefringence). The desired feedback signal may be generated at the output of compensator 25 by monitoring the amount of distortion that is due to the differential time delay present in an optical signal after it has traveled through compensator 25.

[0018] We have recognized that, that in accordance with another aspect of the invention, only one feedback signal is needed to simultaneously adjust the polarization transformation and adjust the differential delay, τ_c, to achieve minimal distortion in the signal that compensator 25 outputs to optical receiver 90 via conventional signal tap 85, as is shown in FIG. 1 and as will be discussed below.

[0019] Specifically, a portion of the signal that compensator 25 outputs is supplied via optical tap 85 to path 87 extending to high-speed photodetector 55, which may be, for example the Hewlett Packard Co., model 11982 Wideband Lightwave Converter having an electrical bandwidth that is at least equal to the information bandwidth of the modulated optical signal transmitted by optical transmitter 10. The remainder of the signal is supplied to path 86 extending to receiver 90. Photodetector 55 converts the high-speed digital information signal modulated onto an optical carrier signal into an electrical signal. The electrical signal is then amplified by conventional amplifier 60 and coupled to electrical distortion analyzer 70 which measures the distortion in the amplified photocurrent and converts the amplified result

electrical power detector 95, which may be, for example, model 8474 diode detector available from the Hewlett Packard Co., more particularly, converts such amplitudes into a single feedback voltage, V_f, that is proportional to the integral of the amplitudes (power levels) of substantially the entire high-frequency electrical spectrum. (It is noted that it is not necessary to include the DC component of the photocurrent in the generation of the feedback voltage, since this component is usually not affected by first order PMD.)

[0026]   For the illustrative embodiment of FIG. 2, the feedback voltage, V_f, generated by the distortion analyzer 70 (FIGs. 1 and 2) may be expressed as follows:

$$V_f = \text{const.} \cdot \int_{f_{min}}^{f_{max}} i_d^2(f) df \qquad (9)$$

where $i_d(f)$ is the amplified version of the photocurrent that photodetector 55 supplies to amplifier 60, f_{min} and f_{max} are respectively the lowest and highest frequencies of the above-mentioned spectrum, in which, preferably, $f_{min} < f_{clock}/100$, where fclock is the clock frequency of the received digital information, and $f_{max} > f_{clock}$. For example, to compensate for a DGD of up to 120 ps in a 10 Gbps transmission system, we found that a f_{min} of $\approx$ 100 MHz and a f_{max} of $\approx$ 15 GHz to be sufficient for deriving a feedback voltage, V_f, having a unique value. To obtain an "unambiguous" feedback signal, it may be necessary to either filter or apply a weighting scheme to the electrical spectrum possibly before or during the aforementioned integration process, based on the spectral components contained in the digital information signal modulated onto the optical signal. In that instance, the output of amplifier 60 is passed through electrical filter 65 before it is detected by power detector 95. This is graphically illustrated in FIG. 3 which shows a graph of the feedback voltage that is obtained by integrating the entire high-frequency spectrum of both unfiltered and filtered 10 Gbps digital information signals, carrying a random or pseudo-random bit sequence (PRBS), versus the total DGD, τ_{total}, experienced by a respective optical signal. Curve 310 shows that the feedback signal derived from an unfiltered optical signal carrying PRBS exhibits secondary maxima at values of τ_{total} above about 180 ps, besides the desired absolute maximum at $\tau_{total} = 0$.

[0027]   Curve 330 of FIG. 3 also shows that appropriate filtering, or weighting, represented by curve 320, of such frequency components removes the undesired secondary maxima and, thus, provides an "unambiguous" feedback signal that may be supplied to polarization transformer 30 and adjustable delay line 50 to provide the desired level of differential time delay in the desired polarization components of the received optical signal. The polarization angle, θ, in polarization transformer 30 and differential time delay, τ_c, in delay line 50 may be adjusted alternately until the level of the feedback signal, V_f, reaches a maximum using a simple maximum search algorithm, such as the algorithm disclosed in the aforementioned U. S. Patent No. 5,212,743. More specifically, the differential time delay in the delay line is continuously dithered around its current value to determine the absolute maximum value of the feedback voltage, V_f. Each time τ_c is set to a different value, the polarization angle, θ, is adjusted by the polarization transformer until the level of the feedback signal, V_f, supplied by distortion analyzer 70 reaches a maximum for that setting. This procedure is repeated for each value of differential time delay, τ_c, until V_f reaches an absolute maximum value, where the distortion due to first-order PMD in the received optical signal is minimized.

[0028]   (Note that Fig. 8 illustrates a distortion analyzer that may be used to derive an "unambiguous" signal corresponding to curve 320.)

[0029]   A second illustrative embodiment of our invention is shown in FIG. 4, and includes a source of optical signals 410, optical transmission fiber 420, and variable DGD compensator 425 formed from two sections each respectively comprising first and second automatic polarization transformer 430 and 440 and first and second high birefringence, single-mode (HBF) fiber 435 and 445 as shown. Fiber 435 (445) may be, for example, the SM.15-P-8/125 fiber having a DGD of about 1.4 ps/m and available from the Fujikura Company (Japan). The sections generate a differential time delay of τ_1 and τ_2, respectively, between the light signals polarized along the slow and fast optical axes of the respective section. The output HBF 445 is coupled to an optional tap 485 connected to optical receiver 490. A portion of the optical signal is fed via tap 485 to high speed photodetector 455. Similarly, the electrical output of photodetector 455 is supplied to amplifier 460 and the amplified result is then supplied to distortion analyzer 470 comprising electrical filter 465 and broadband electrical power detector 495, which generates a feedback signal that is supplied to polarization transformer 430 and polarization transformer 440.

[0030]   Polarization transformer 440 in response to the feedback signal rotates the state of polarization of the optical signal between HBF 435 and HBF 445 such that transformer 440 effectively varies the angle, θ_c, between the fast axis of HBF 435 and the fast axis of HBF 445. The resulting differential time delay, τ_c, provided by the cascading of HBF

where $\Delta\omega = \omega - \omega_o$, and $\underline{W}(\theta)$ is the polarization transformation in polarization transformer 430. It is seen from equation (11) that for $\tau_c = 2\tau_1 \cdot \cos\theta_c$ and to a first order in $\Delta\omega$, $U_{comp}(\omega)$ has the same desired form of Eq. (7). However, the off diagonal terms in the second matrix on the right side of Eq. (11) show that for large values of $\tau_1\Delta\omega$, a significant amount of light is cross coupled between the PSP of the compensator. Specifically, at $\theta_c = \pi/4$ radians and $\tau_1\Delta\omega = \pi$ radians, the light from either one of the input PSP is completely coupled to the orthogonal output PSP.

[0034] Thus, if the total bandwidth of the optical signal is large compared with either $1/\tau_1$ or $1/\tau_2$, then compensator 425 would not be capable of simultaneously generating the desired differential time delay for all frequency components of the optical signal to offset the effects of first-order PMD in the transmission fiber.

[0035] However, we have shown experimentally that for an amplitude-modulated optical signal carrying a pseudor-andom 10 Gbps digital signal, a differential time delay of $\tau_1 \cong \tau_2 \cong 50$ps generated by compensator 425 still allowed for an adaptive PMD compensation with acceptable low levels of second-order PMD distortion

[0036] Note that compensator 425 may be readily arranged to generate a differential time delay greater than $\tau_c = \tau_1 + \tau_2 = 100$ ps by merely adding additional sections, as needed, in which, as mentioned above, each such additional section comprises a polarization transformer and HBF with differential time delays of $\tau_3 = 50$ ps, $\tau_4 = 50$ ps, and so on. Such a compensator is also capable of compensating for the effects of second-order PMD in addition to first-order DGD.

[0037] A broad block diagram of another illustrative embodiment of an adjustable differential delay line operative for compensating for variable first-order PMD is shown in FIG. 5. Similarly, as shown in FIG. 1, the compensator system of FIG. 5 includes an element 540 at the input to split (separate) the polarization of an incoming optical signal and an element 541 at the output to recombine the transformed PSP of the transmission fiber. A variable time delay associated with one of the PSP is generated by a number of asymmetric, waveguide Mach-Zehnder interferometers 530 through 532 connected in series via adjustable directional couplers 560 through 563, respectively. The directional couplers may be controlled in a conventional manner to direct the optical signal either through the short or long leg of the Mach-Zehnder interferometers 530 through 532, thereby introducing a variable delay between 0 (zero) and $\tau_i = \Delta L_i \cdot n/c$; where $\Delta L_i \cdot n$ is the optical path difference in the i-th interferometer and c is the speed of light. It is thus possible to generate any desired differential time delay between 0 (zero) and $\tau_{cmax} = (2^n - 1) \cdot \Delta L_i n/c$ in discrete steps of $\Delta\tau_c = \Delta L_1 n/c$.

[0038] To obtain an uninterrupted flow of the signal through the interferometers while the delay τ_c is being changed from one value to another, the relative optical phases in each of the interferometers need to be changed for constructive in-phase interference of the two optical signals which emerge from the two arms of each Mach-Zehnder interferometer and then enter the succeeding directional coupler. Therefore, it may be necessary to include a variable phase shifter, e.g., a respective one of the phase shifters 570 through 572, in each of the Mach-Zehnder interferometer.

[0039] A controllable waveguide delay line based on the foregoing principles may be readily constructed on a number of different electrooptic substrates, such as, for example, lithium niobate and semiconductor materials as well as other optical materials using, for example, thermo-optic or acousto-optic effects to control the directional couplers 560 through 563 and phase shifters 570 through 572.

[0040] It is noted that, for the PMD compensators shown in FIGs. 1 and 4, a very low level of distortion might occur in the signal that the transmission fiber outputs if most of the signal that is transmitted in one of the PSP of the fiber, i.e., if γ or $(1- \gamma)$ is small. Also S(f) would be close to 1, even if a large value of τ_f is present in the transmission fiber. In that event, τ_c in the compensator would have some arbitrary value. Further, the level of distortion in the optical signal might become suddenly large if the state of polarization of the optical signal changes rapidly at some point along the fiber, thereby requiring rapid adjustment of the values of θ and τ_c in the PMD compensator.

[0041] The sudden adjustment of τ_c may be avoided by rapidly scanning the input state of polarization to the trans-mission fiber over a large number of different polarization states, such that, for example, averaged over time, all possible polarization states are excited with equal probability. Then, approximately one-half on the input signal, on average, would be in one of the PSP of the transmission fiber and the other one-half would in the other PSP, i.e., on average $\bar{\gamma}$ = 0.5 = 1-$\bar{\gamma}$. Consequently, a sufficient level of distortion is consistently present in the optical signal supplied to the PMD compensator to ensure that τ_c is adjusted properly independent of changes in polarization in the corresponding fiber.

[0042] To ensure that the feedback circuit in the PMD compensator remains stable, the aforementioned scanning of the input polarization state to the transmission fiber has to be performed much faster than the response time of the polarization transformer that serves as the input to the PMD compensator. One example capable of performing such scanning is the electro-optic polarization scrambler disclosed in U. S. Patent No. 5,359,678 issued October 25, 1994 to F. Heismann et al, which is hereby incorporated by reference.

[0043] FIG. 7 shows an illustrative embodiment of the invention that uses a fast-electro-optic polarization scrambler 15 at the input of the transmission fiber. Scrambler 15 may be modulated with an arbitrary voltage, e.g., a sinusoidal or sawtooth voltage, as long as the average degree of polarization of the light signal that scrambler 15 outputs is substantially equal to zero.

[0044] The foregoing is merely illustrative of the principles of the invention. Those skilled in the art will be able to devise numerous arrangements, which, although not explicitly shown or described herein, nevertheless embody those

a variable optical birefringence element connected in series with the transmission line for generating a differential optical time delay between selectable mutually orthogonal polarization states,

an optical signal analyzer coupled to an output of the variable birefringence element for generating a control signal proportional to the total differential optical time delay in an optical signal at the output of the variable birefringence element, and

a feedback element for controlling the amount of differential time delay generated in the variable birefringence element and for selecting the two orthogonal polarization states in the variable birefringence element in response to the control signal generated by the optical signal analyzer.

12. The apparatus of claim 11 wherein the variable birefringence element comprises

a variable polarization transformer for transforming two selected orthogonal polarization components of the optical signal entering the polarization transformer into two predetermined orthogonal polarization states, and

a variable birefringence element connected to the output of the polarization transformer for generating a variable differential time delay between said two predetermined polarization states.

13. The apparatus of claim 12 wherein the variable birefringence element comprises

a polarization splitter connected to the output of the polarization transformer for separating the two predetermined polarization components into two spatially separated optical paths,

a variable differential delay line connected to the outputs of the polarization splitter for generating a variable differential time delay between the two predetermined polarization components, and

a polarization combiner connected to the outputs of the variable differential delay line for combining said predetermined differentially delayed polarization components into two mutually orthogonal polarization states of a single optical output signal.

14. The apparatus of claim 11 wherein the variable birefringence element comprises

a first variable polarization transformer for transforming two selected orthogonal polarization components of the optical signal entering the polarization transformer into two controllably variable orthogonal polarization states,

a first fixed birefringence element connected to the output of the first polarization transformer for generating a first predetermined differential time delay between two predetermined orthogonal polarization components,

a second variable polarization transformer connected to the output of the first fixed birefringence element for transforming two selected polarization components of the optical signal entering the second polarization transformer into two controllably variable orthogonal polarization states, and

a second fixed birefringence element connected to the output of the second polarization transformer for generating a second predetermined differential time delay between two predetermined orthogonal polarization states.

15. The apparatus of claim 14 wherein the first and second differential time delay in the first and second fixed birefringence elements are substantially equal.

16. The apparatus of claim 14 wherein the first and second fixed birefringence elements are respective predetermined lengths of birefringent optical fiber.

17. The apparatus of claim 11 wherein the variable birefringence element comprises N sections connected in series, where N > 1,
each said section comprising:

receiver including an analyzer operative for generating a control signal having a value proportional to the value of the differential time delay, said receiver changing the value of the differential time delay and selection of the two orthogonal polarization states as a function of the current value of the control signal and doing so until the value of the control reaches a predetermined level.

27. The system of claim 26 wherein said receiver comprises a variable birefringence element.

28. The system of claim 27 wherein the variable birefringence element comprises

a variable polarization transformer for transforming two selected orthogonal polarization components of the optical signal entering the polarization transformer into two predetermined orthogonal polarization states, and

a differential time delay line connected to the output of the polarization transformer for generating a variable differential time delay between said two predetermined polarization states.

29. The system of claim 28 wherein the variable birefringence element further comprises

a polarization splitter connected to the output of the polarization transformer for separating the two predetermined polarization components into two spatially separated optical paths, in which the variable differential delay line is connected to respective outputs of the polarization splitter for generating a variable differential time delay between the two predetermined polarization components, and

a polarization combiner connected to the outputs of the variable differential delay line for combining said predetermined differentially delayed polarization components into two mutually orthogonal polarization states of a single optical output signal.

30. The system of claim 27 wherein the variable birefringence element comprises

a first variable polarization transformer for transforming two selected orthogonal polarization components of the optical signal entering the polarization transformer into two controllably variable orthogonal polarization states,

a first fixed birefringence element connected to the output of the first polarization transformer for generating a first predetermined differential time delay between two predetermined orthogonal polarization components,

a second variable polarization transformer connected to the output of the first fixed birefringence element for transforming two selected polarization components of the optical signal entering the second polarization transformer into two controllably variable orthogonal polarization states, and

a second fixed birefringence element connected to the output of the second polarization transformer for generating a second predetermined differential time delay between two predetermined orthogonal polarization states.

31. The system of claim 30 wherein the first and second differential time delay in the first and second fixed birefringence elements are substantially equal.

32. The system of claim 30 wherein the first and second fixed birefringence elements are respective predetermined lengths of birefringent optical fiber.

33. The system of claim 26 wherein the variable birefringence element comprises N sections connected in series, where N > 1,
each said section comprising:

a variable polarization transformer for transforming two selected orthogonal polarization components of the optical signal entering the polarization transformer into two controllably variable orthogonal polarization states, and

a fixed birefringence element connected to the output of the polarization transformer for generating a prede-
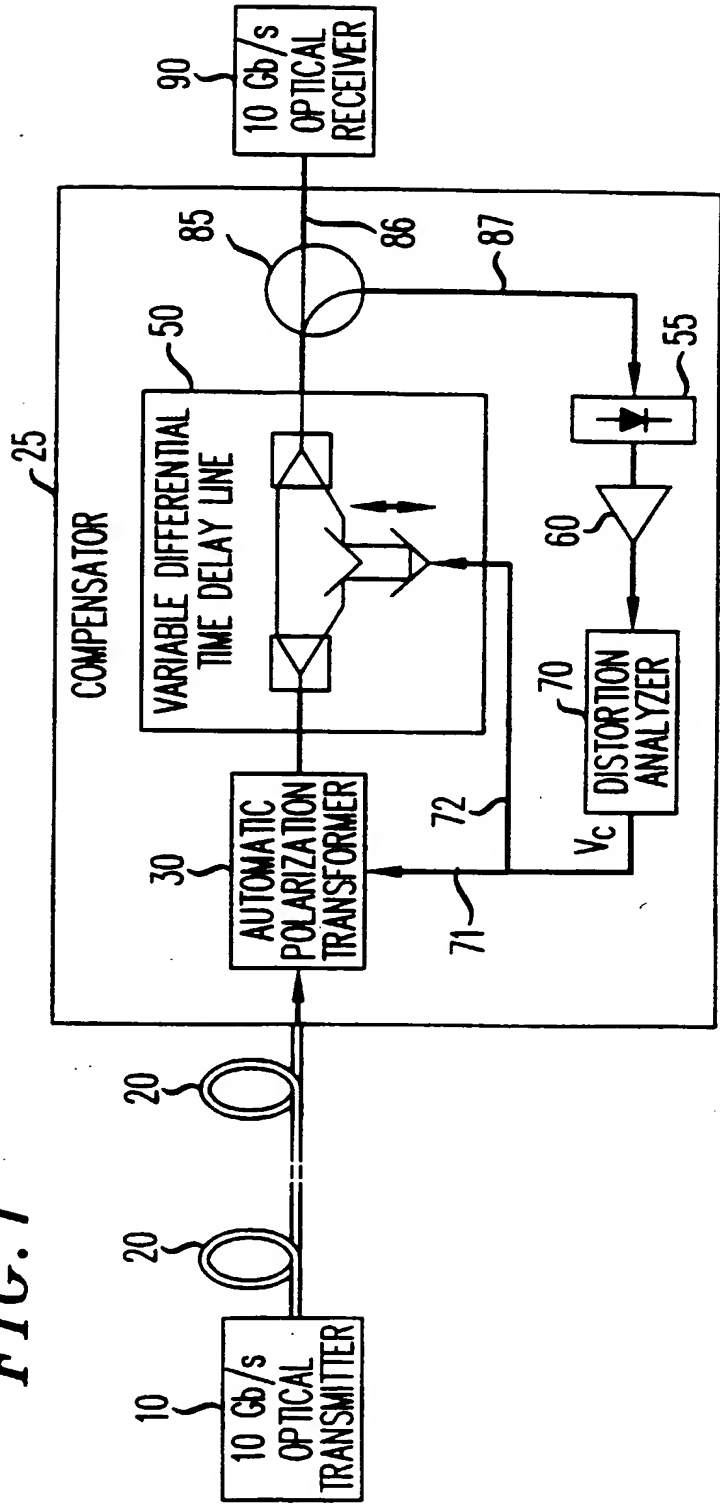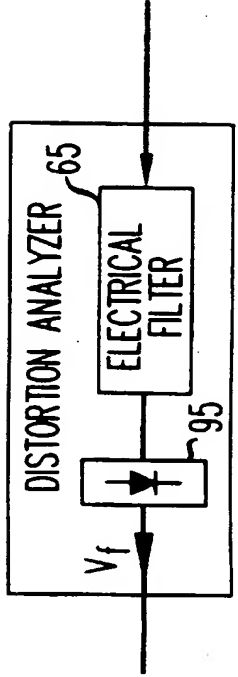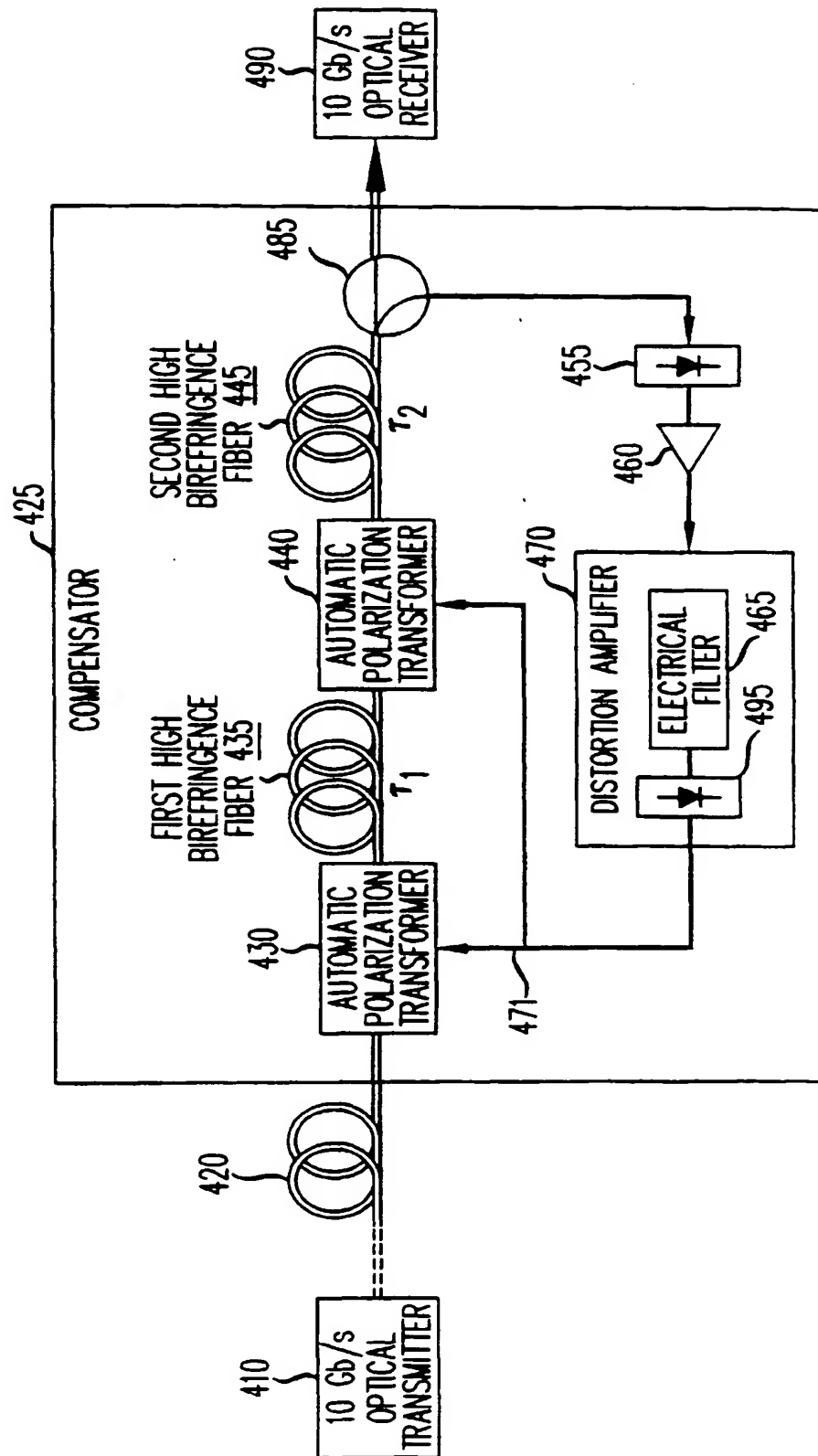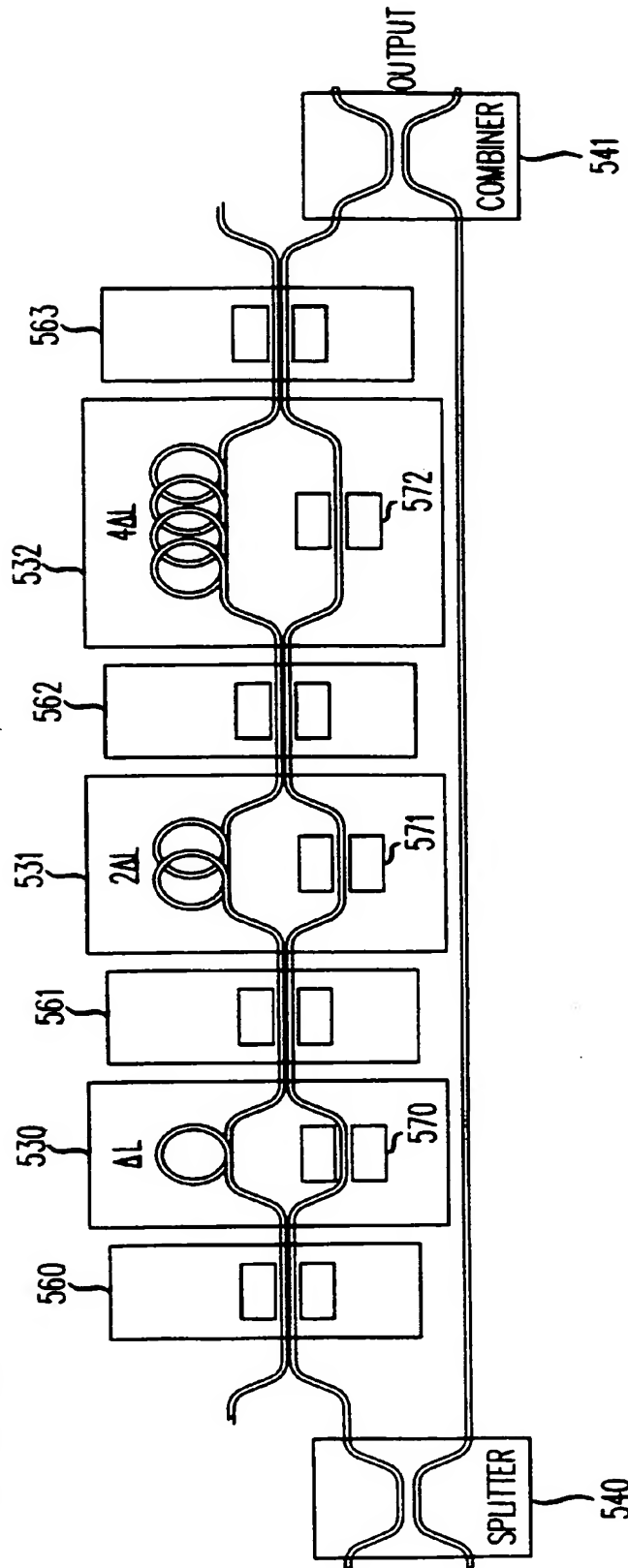
FIG.1

FIG.2

FIG. 4

FIG.6

FIG.8